Transverse matching of MEBT to DTL tank 1 using rms emittance or rms beam size from DTL diagnostic plate

SNS/AP TECHNICAL NOTE

Number 09

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1. Introduction

During the commissioning, diagnostics data will be used to obtain matching, to find various set points, and trajectory correction etc. Possibilities are studied through simulation to obtain transverse and/or longitudinal matching of MEBT to DTL tank 1, using rms emittances or rms beam sizes. When commissioning DTL tank 1, a diagnostic beam line called Diagnostic plate will be installed at the end of DTL tank 1. Diagnostic plate is equipped with various diagnostics devices such as BPMs, wire-scanners, slit and collectors for emittance measurements, toroid, and a Faraday cup with energy degrader, etc. And these devices, together with in-line or off-line analysis tools, provide necessary data for commissioning. Because a certain level of machine imperfections is unavoidable during manufacturing, the real machine is somewhat different from the model. Under these conditions, it becomes quite necessary to test at least through simulation whether it is feasible to obtain matching from the MEBT to DTL tank 1 using rms emittances or rms beam sizes.

All simulations are done using a realistic initial beam distribution just before the four MEBT matching quadrupoles. The initial beam distribution consists of 10000 macro particles and is well matched. MEBT quadrupoles or DTL tank 1 rf phase and amplitude are varied and rms emittance or rms beam size is taken from the Parmila output file at the end of DTL tank 1.

In simulation test, optimization is done using a minimization routine of MATLAB®. This routine uses the simplex search method of [1]. This is a direct search method that does not use numerical or analytic gradients. The maximum allowed iteration number is set to 150. The whole process of writing a new Parmila input file, running Parmila, and reading in rms emittances from output files of Parmila is automated.

2. Matching using rms emittances without machine imperfections

The possibility of matching from the MEBT to DTL tank 1 using measured rms emittances is studied. To this end, the behavior of rms emittance with respect to quadrupole gradients is investigated first to see what can be expected and what the system is like. And simulation experiment is carried out to see how close matching can be done using the optimization routine.

rms emittance vs. matching quadrupole gradient

The behavior of rms emittances with respect to the gradient change of the four MEBT matching quadrupoles and rf phase and amplitude offset of DTL tank 1 are studied. Figures 1 and 2 indicate that rms emittance is minimum when matching is done and that there exists only one minimum. In the case where DTL tank 1 rf amplitude and phase are varied (see Figs 3 and 4), this alters transverse matching due to the change of transverse rf defocusing force and the design matched condition is no longer matched.

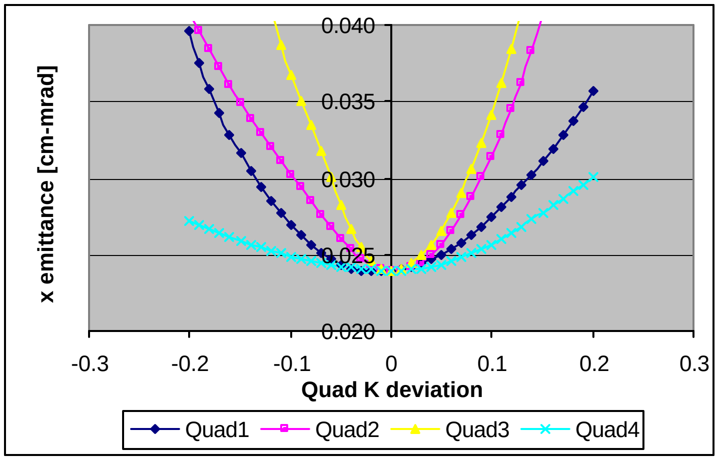

FIG. 1. Plots of x emittance in cm-mrad with respect to the change of quadrupole gradient. 0.1 on x-axis means quadrupole strength is off by +10% of design value. When the gradient of quadrupole 1 is varied, the gradients of the rest three quadrupoles are set to its design values.

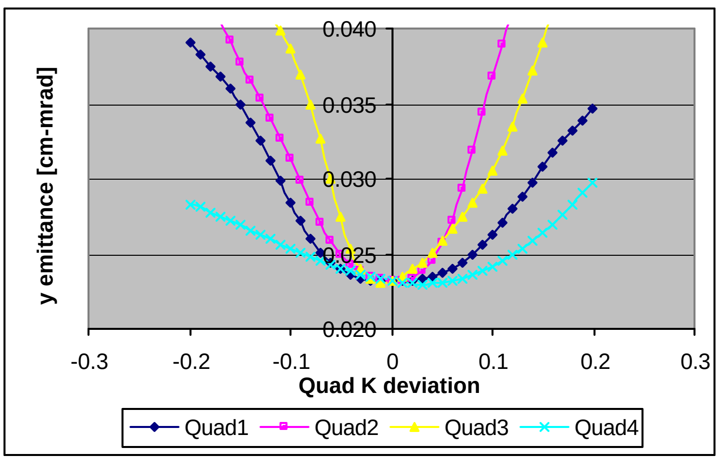

FIG. 2. Plots of y emittance in cm-mrad with respect to the change of quadrupole strength. 0.1 on x-axis means quadrupole strength is off by +10% of design value. When the gradient of quadrupole 1 is varied, the gradients of the rest three quadrupoles are set to design values.

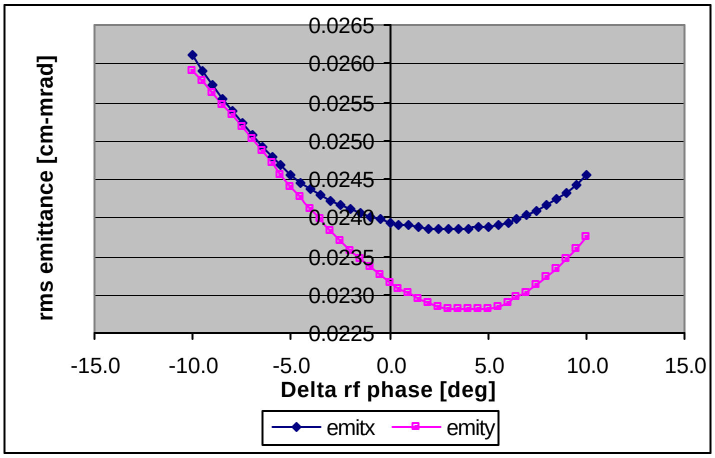

FIG. 3. Plots of x and y emittance with respect to the rf phase of DTL tank 1. 5.0 degrees means that rf phase of DTL tank 1 is off by 5 degrees from the design value.

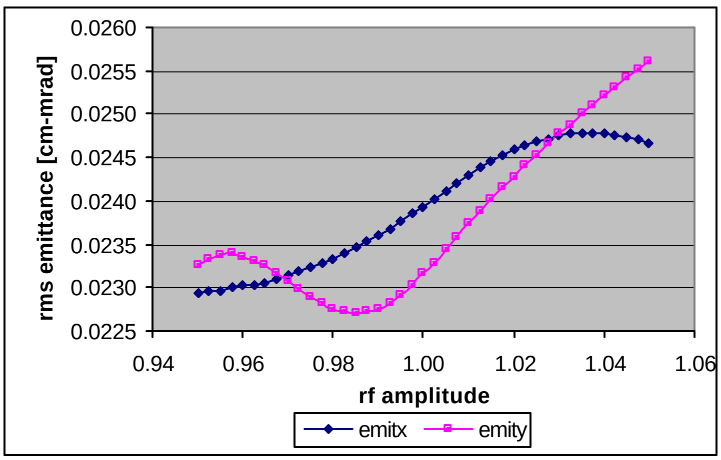

FIG. 4. Plots of x and y emittance in mm-mrad with respect to the rf amplitude of DTL tank 1. 0.98 means that rf amplitude is at 98% level of design value.

Transverse matching using rms emittances

During the commissioning, rms emittance will be measured using slit and collector located in the diagnostic beam line called Diagnostic plate to be located at the end of DTL tank 1. 10 to 20% measurement errors are anticipated. The effect of the emittance measurement errors is included in the simulation. In the simulation, the program reads in the rms emittance values from the Parmila output file and adds random errors to them. These values are used by the optimizing routine. Machine imperfections are not included here. Simulation results with machine imperfections are presented in the next section.

Through simulation, it is tested how close the rms emittances can be set to the design values. Two different arbitrary MEBT matching quadrupole gradient vectors are used as initial conditions, which are denoted as initial quadrupole set 1 and 2 in Fig. 5. For both quadrupole gradient vectors, $|\mathbf{V}-\mathbf{V_o}|/|\mathbf{V_o}|$=4.756% where **V** is the initial quadrupole gradient vector (called initial quadrupole set 1 and 2) and $\mathbf{V_o}$ is the design gradient vector.

Figure 5 shows the x and y rms emittances after optimization vs. various levels of measurement error from 0% to 20%. 20% error on x-axis means 20% emittance measurement error, which means that 3σ of normal error distribution are equal to 20% of the measured quantity. Compared with design values, **A Reasonable level of transverse matching can be accomplished using rms emittances**. 20% measurement error seems tolerable.

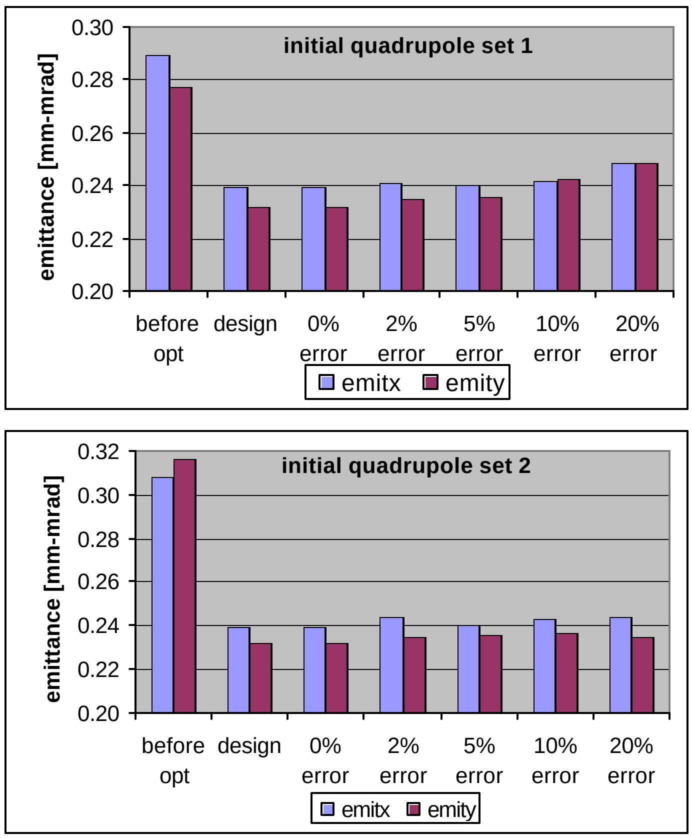

FIG. 5. Plots of rms emittances vs. emittance measurement errors. 20% error means that 20% measurement error is included in rms emittance values, which means that 3σ of normal error distribution are equal to 20% of the quantity.

Transverse and longitudinal matching using rms emittances

The possibility of performing both transverse and longitudinal matching using transverse rms emittances is also studied. **The matching optimization is not so successful in this case** because changing rf amplitude and phase alters rf transverse defocusing. Due to the change in transverse defocusing, the optimum transverse emittance changes.

3. Matching using rms emittances with machine imperfections

When commissioning, the DTL and MEBT will have a certain level of machine imperfections. Also the design matching condition obtained from the model may not be correct. And we may not know what the design x and y emittance should be. As a result, an alternative technique is studied. Considering the properties of a matched beam in the rms sense, the x and y rms emittances will be minimum when matching is properly done. Optimization is done in such a way that x and y rms emittances are minimized. The optimization result in Fig. 6 is obtained after 150 iterations.

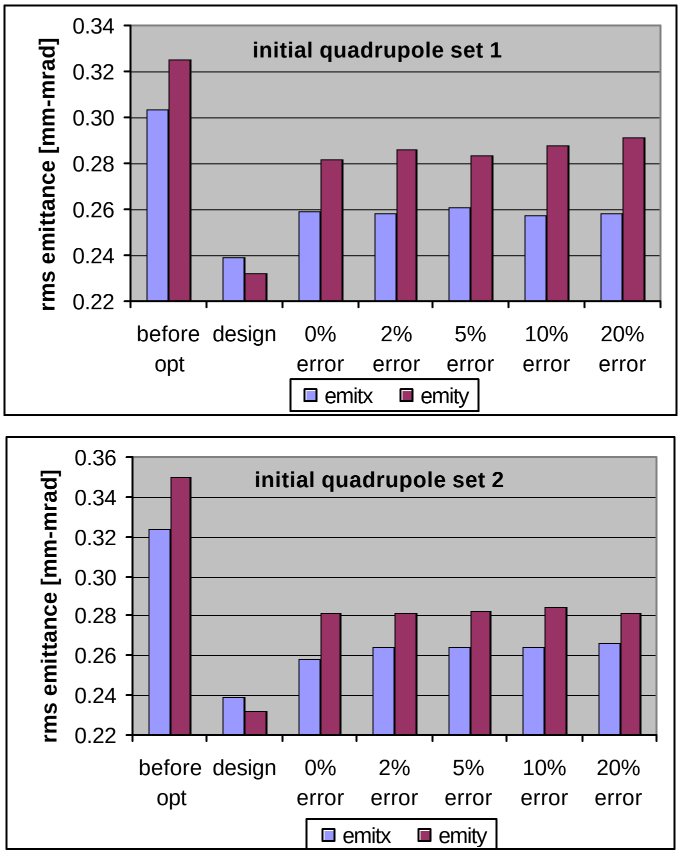

FIG. 6. Plots of x and y rms emittances vs. various measurement errors. This is obtained with the inclusion of machine imperfections for two different initial MEBT matching quadrupole gradients. This is a result of 150 iterations. Design x (y) rms emittance is 0.2394 (0.2318) mm-mrad without machine imperfections. 5% error on x-axis means that a 5% measurement error is included in the rms emittance values, meaning that 3σ of normal error distribution are equal to 5% of the quantity.

Table I: Machine imperfections included

Quad roll (deg)	Quad tilt x (deg)	Quad tilt y (deg)	Δx (mm)	Δy (mm)
0.25	0.57	0.57	0.127	0.127
Rf phase (deg)	Rf amplitude			
0.5	0.5%			

Table I lists the machine imperfections included in the simulations. **Simulation test indicates that a reasonable transverse matching can be expected using measured rms emittances with the inclusion of machine imperfections and rms emittance measurement errors**. For two different sets of initial MEBT quadrupole gradient vectors, the result is consistent. One interesting fact is that optimized rms emittances are rather insensitive to rms emittance measurement error being 0%, 2%, 5%, 10% or 20%. Here 5% error means that 3σ of normal error distribution are equal to 5% of the quantity. One point worthy to note is that matched rms emittances are rather insensitive to emittance measurement error levels used during optimization. The final emittance is about 15 to 20% greater than the design values.

When only 50 iterations of measurements are done, the following optimization result is obtained. The result is quite close to the 150-iteration result in Fig. 6.

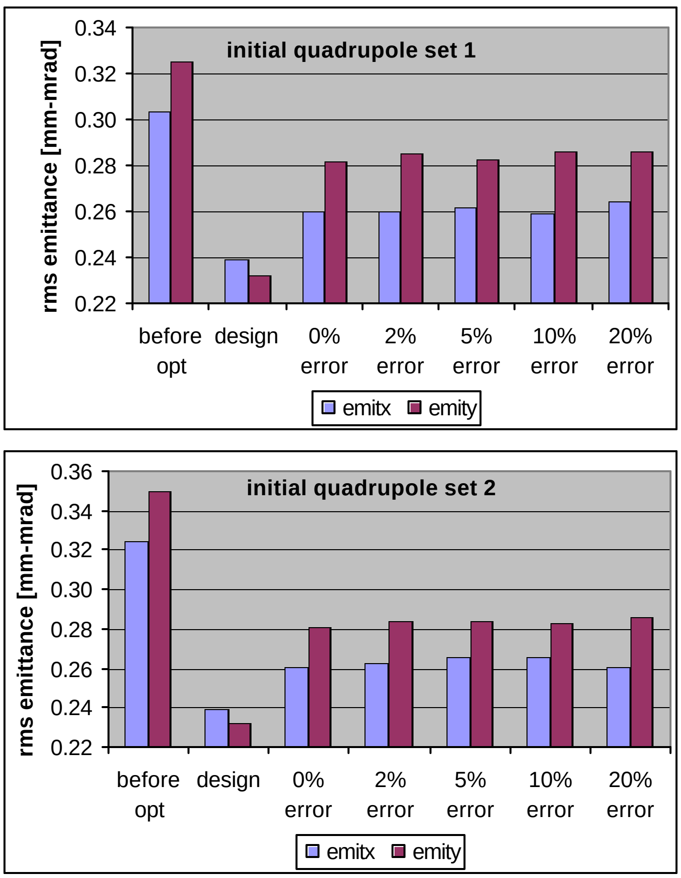

FIG. 7. Plots of x and y rms emittances vs. various measurement errors. This is obtained after 50 iterations of measurements with the inclusion of machine imperfections for two different initial MEBT matching quadrupole gradients.

4. Matching using rms beam sizes without machine imperfections

As an alternative to using rms emittances, the possibility of performing transverse matching between MEBT and DTL tank 1 using rms beam sizes from wire-scanners. To this end, the behavior of rms beam sizes with respect to the gradient change of MEBT quadrupoles is studied.

Behavior of rms beam sizes

The behavior of rms beam sizes is investigated with respect to the four matching quadrupole gradients at the end of MEBT. Figures 8 to 11 strongly indicate that there could be more than one MEBT quadrupole gradient vector that generates the prescribed x and y rms beam sizes. And the variation of rms beam sizes is quite nonlinear.

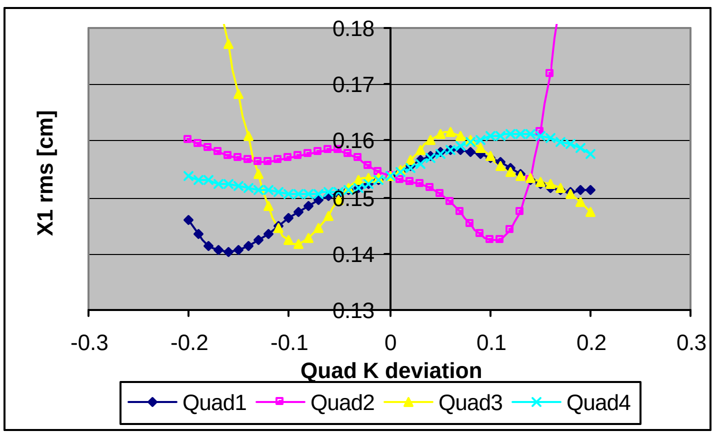

FIG. 8. x rms beam size [cm] vs. quadrupole strength change. The wire scanner is located at the end of DTL tank 1. 0.1 Quad K deviation means that quadrupole gradient is 110% of design value (that is 10% more).

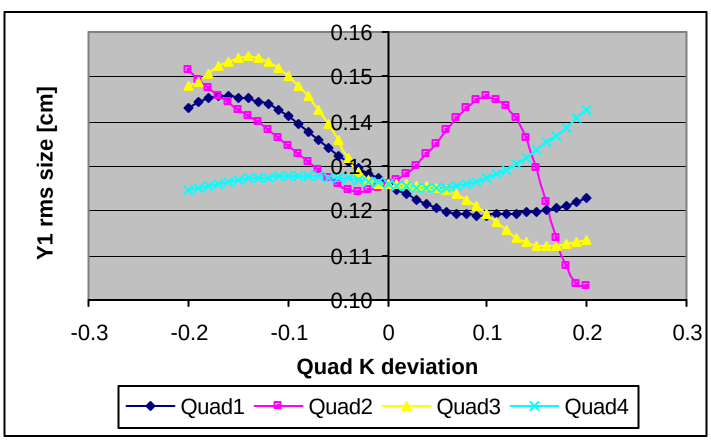

FIG. 9. y rms beam size [cm] vs. quadrupole strength change. The wire scanner is located at the end of DTL tank 1.

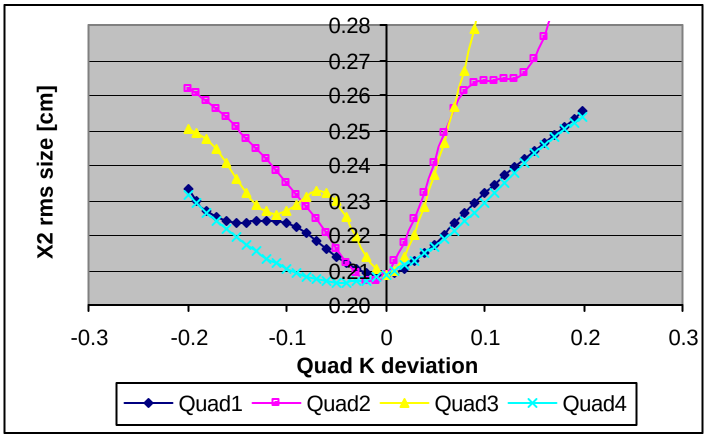

FIG. 10. x rms beam size [cm] vs. quadrupole strength change. The wire scanner is located in the Diagnostic plate at the end of the DTL tank 1.

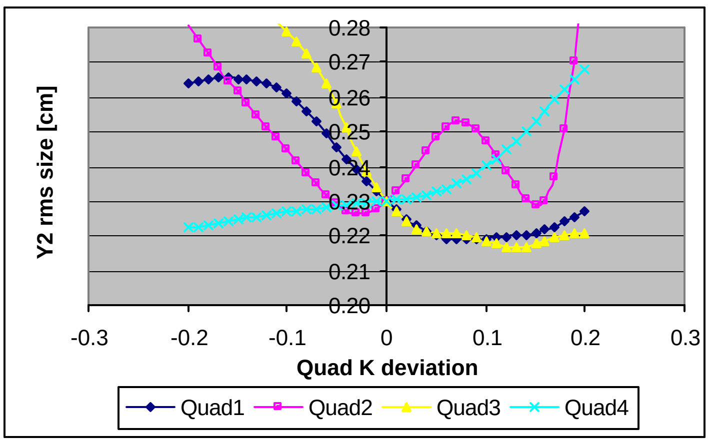

FIG. 11. y rms beam size [cm] vs. quadrupole strength change. The wire scanner is located in the Diagnostic plate at the end of the DTL tank 1.

Optimization results

As is expected, **optimization results are not so encouraging** due to the existence of more than one quadrupole gradient vector that generates the prescribed rms beam sizes from two wire scanners. In commissioning, this approach may not be so practical in obtaining transverse matching. **Another problem is that the rms beam size depends sensitively on detailed optics of the real machine**. The real machine includes various machine imperfections and may result in quite a different machine from the model. In commissioning the SNS warm linac, it is unlikely that we know the exact optics of the linac. And we do not know what the reference rms beam size should be. So there is a problem in setting the target values of rms beam size when doing optimization. As is shown in Fig. 12, rms emittance values vary a lot depending on initial conditions of MEBT matching quadrupole gradients (i.e. initial quadrupole set 1 and 2) and also on the measurement errors. It also turns out that rms emittance values vary significantly depending on random numbers used to simulate measurement errors. For example, rms emittance values vary from (ε_x=0.2872, ε_y=0.2822) to (ε_x=0.2541, ε_y=0.2427) for a 5% measurement error when using different sequence of random numbers.

It should be also noted that rms emittances for 0% measurement error are quite different from design rms emittances in the top plot of Fig. 12. However, rms beam sizes for 0% measurement error are exactly same as design values, which means that the solution is not unique. For the bottom plot of Fig. 12, rms emittances are quite different from design values for 5%, 10% and 20% measurement errors, which is another sign that the solution is not unique.

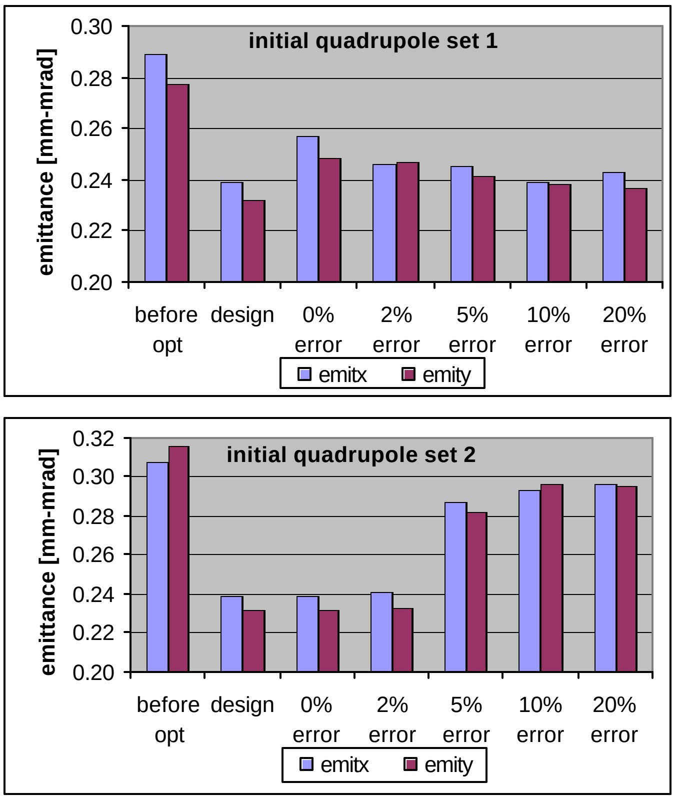

FIG. 12. Plots of x and y rms emittances vs. measurement errors. This is obtained for two different initial MEBT matching quadrupole gradients without the inclusion of machine imperfections. Design x (y) rms emittance is 0.2394 (0.2318) mm-mrad without machine imperfections. 20% error on x-axis means that 20% measurement error is included in rms beam size values, meaning that 3σ of normal error distribution are equal to 20% of the quantity.

5. Conclusion

Possibilities of performing transverse matching using measured rms emittance and using measured rms beam size are studied. **Automated simulation test indicates that reasonable level of transverse matching can be obtained using measured rms emittances by minimizing rms emittances**. **One advantage is that this approach does not require the knowledge of detailed optics information of real machine**. One point worthy to note is that matched rms emittances are rather insensitive to emittance measurement error levels used during optimization due to robustness of the optimizer.

Using measured rms beam size is not so promising due to the fact that there could be more than one solution, that is, there exist more than one MEBT quadrupole gradient vector that generates the prescribed rms beam sizes. **Another problem is that rms beam size depends sensitively on detailed optics of real machine**. Real machine includes various machine imperfections and may result in quite a different machine from the model. In commissioning SNS warm linac, it is likely that we do not know the exact optics of linac. And we do not know what the reference rms beam size should be when matched perfectly.

[1] Lagarias, J.C., J. A. Reeds, M.H. Wright, and P.E. Wright, "Convergence Properties of the Nelder-Mead Simplex Algorithm in Low Dimensions," May 1, 1997. To appear in the SIAM Journal of Optimization.